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Project Note

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Executive summary

This study assesses the impact that Waratah Dam has on attenuating flood peaks in its catchment. TasWater requested Entura to assess the attenuation capacity of the reservoir at the 1:50 (2%) annual exceedance probability (AEP). It is noted that piping through the dam embankment at a level of 606.6 m AHD (Australian Height Datum 1983) was detected in 2017, warranting an emergency excavation of the spillway to protect the safety of the dam. The impact of attenuation has been assessed under conditions that existed prior to the emergency spillway excavation.

An update to flood frequency estimation at the site shows that flood peak inflows are lower than previous estimates.

Recent site survey (including bathymetry) shows that elevations of the dam crest and spillway invert differ from previous estimates. The storage-volume curve of the reservoir has been updated accordingly.

A hydraulic model has been developed of the dam's spillway and a new rating has been developed in its pre-2017 (ie prior to excavation) condition. The capacity of the spillway when reservoir levels are at the dam crest is estimated to be 15 m^3/s, which is higher than previous estimates, though its capacity below the level at which the piping hole formed is very low (~1.5 m^3/s). Waratah Dam, with the spillway in its pre-2017 condition, does attenuate flood peaks by varying amounts depending on the nature of the storms. The magnitude of attenuation varies considerably due to different storm conditions (duration, intensity/depth and temporal pattern).

Under the modelling conditions, the flood caused by the mid-range 1:50 AEP, 9 hour storm, the no dam scenario has a peak of approximately 13.3 m^3/s. From the same design storm, the dam outflow has a peak of approximately 4.7 m^3/s with a peak reservoir level of 606.92 m AHD. It should be noted that failure of the dam at full supply level or close to dam crest level will result in much high flows and levels in Waratah township than caused by the loss of flood attenuation if the dam was removed.

Nonetheless, the dam crest flood prior to spillway lowering of approximately 1:400 AEP with zero freeboard. This is less than the ANCOLD (2000) recommended flood capacity requirements for a Significant Consequence Category dam (Entura 2017a) of between 1:1,000 and 1:10,000 AEP plus freeboard for wave action. Thus, although the dam provides significant flood attenuation at the 1:50 AEP flood, the risks associated with flood overtopping failure are unacceptably high and the spillway capacity should be upgraded or the dam decommissioned as a matter of urgency. In addition, due to the known piping hole at approximately RL606.6m AHD, this level should be targeted rather than the dam crest of the for an interim spillway upgrade. The AEP of exceeding the level of the piping hole is estimated to be around 1:2 to 1:5. Entura has not carried out modelling to identify the extent of spillway lowering and widening required to pass the ANCOLD (2000) design flood requirements below the level of the known piping hole. It is recommended that further investigations for providing adequate flood protection for the dam be undertaken.

Background

TasWater is considering decommissioning Waratah Dam in north western Tasmania, and is seeking an understanding of the flood mitigation and attenuation impacts the dam has on downstream flooding in Waratah. This study has addressed this question through the following method:

1. Determine the natural (non-dam) flood frequency curve using a regional method and comparing to nearby gauge data
2. Develop a rainfall/runoff model to estimate flood events comprising of catchment and reservoir routing components too account for flow response and attenuation. The model has been validated against the flood frequency curve
3. Run the model with a range of design rainfalls using both catchment and reservoir routing components.
4. Also run the model with flow hydrograph inputs, scaled from nearby catchments and apply the reservoir routing component only
5. Assess peak flood discharges downstream of Waratah Dam for two scenarios:
    (a) With the dam in place and start storage at FSL, assuming that the de-watering pipe is not operating
    (b) Without the dam

Description of the Dam

Waratah Dam has a capacity of approximately 800 ML at Full Supply Level (FSL) and a catchment area of approximately 10 km^2 (Hydro Tasmania Consulting 2010). The capacity of the spillway with the reservoir water level at the dam crest level, prior to excavation works in 2017, was estimated by Hydro Tasmania Consulting (2010) to be 5.3 m^3/s with water in the reservoir 0.8 m above the spillway invert. There is considerable uncertainty with this estimation, and Hydro Tasmania Consulting (2010) had recommended detailed site survey, and a hydraulic assessment to confirm the capacity of the spillway capacity. There has been no record of flood overtopping the dam crest since the dam was repaired in 1976, and no signs of overtopping were visible during recent inspections (Entura 2013) although the crest of the dam was reached during the 2017 event.

It is understood that during 2017, emergency excavation of the spillway took place to lower the FSL of Waratah Dam below a level at which piping incident had occurred at a level of 606.6 m AHD[1]. Waratah Dam FSL, both currently and prior to the emergency work, are presented as 'current survey' in Table 1.

Critical reservoir levels estimated from previous studies (Hydro Tasmania Consulting 2010; Entura 2013) differ considerably from a recent site survey completed by Entura: comparisons of critical levels are given in Table 1. The recent survey incorporated previous survey data from 2014 which had captured the invert level of the spillway prior to the excavation works.

Table 1 Comparison of previous estimates of critical levels at Waratah Dam and surveyed levels (AHD)

	Previous studies (HTC[2] 2010)	**Current survey**
Dam Crest[1]	608.8 m	607.5 m
Spillway invert/FSL (pre-2017)	608.0 m	606.3 m
Spillway invert/FSL (current condition)	*NA*	605.2 m
FSL to dam crest (pre-2017)	0.8 m	1.2 m

The difference in levels is considerable. It has been decided to adopt the levels from the recent survey results in this study, as they are considered to be more accurate.

The storage curve of Waratah Dam was approximated by Entura (2013) from small scale mapping, satellite photography and provided information of the dam's capacity and dimensions. This storage curve has been offset by -1.7 m to align it with the current survey; this preserves the notional storage capacity of 800 ML at FSL. This updated storage curve is given in Figure 1.

[1] All elevations in this report are given in metres Australian Height Datum 1983 (AHD)

[2] Hydro Tasmania Consulting

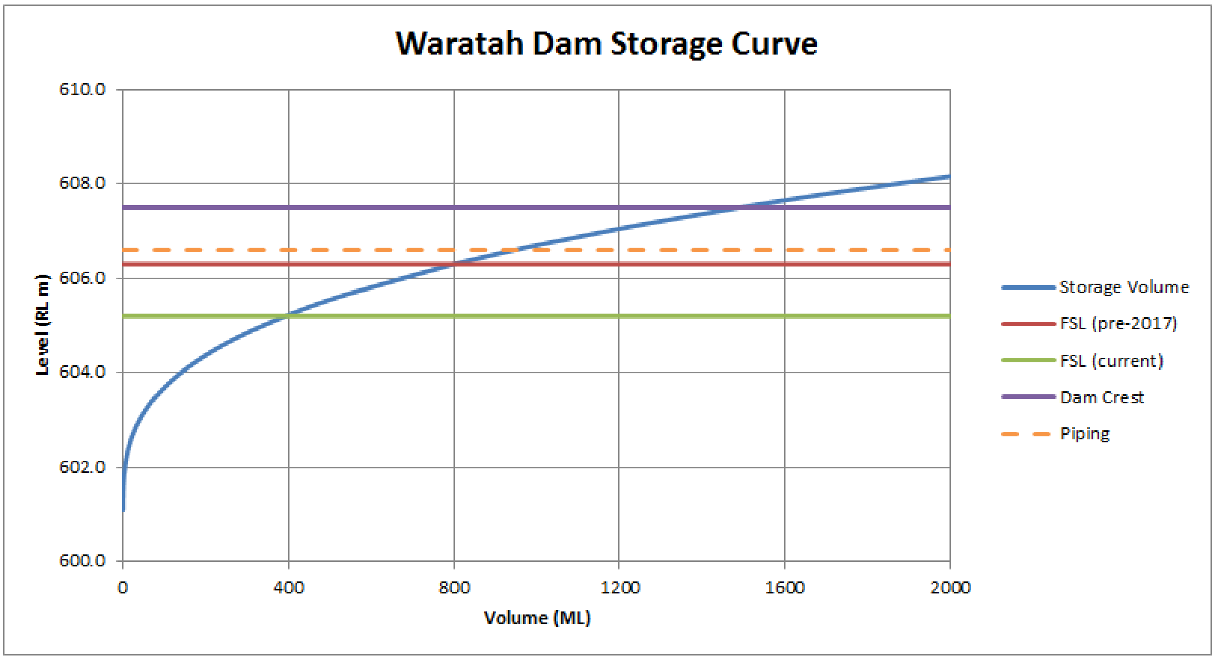

Figure 1 Updated storage curve for Waratah Dam with critical levels (levels in mAHD)

Spillway rating development

Hydro Tasmania Consulting (2010) noted that the estimate of the spillway's capacity was approximate and recommended a detailed study to confirm the spillway capacity. With the available survey data and bathymetry, a more rigorous spillway rating has been developed using hydraulic models as part of this study.

A level-discharge spillway rating was developed for Waratah Dam in the pre-2017 configuration. Site survey was available from 2014 and 2018. The 2014 survey included bathymetry of much of the spillway chute but not of the spillway crest or the reservoir itself (see Figure 2 for survey extents). As such, the 2014 site survey has been merged with the 2018 bathymetry. Several assumptions were made when merging the 2014 survey with the 2018 survey, resulting in some uncertainty as to the exact bathymetry in the pre-2017 condition. Resulting profiles of the spillway using the generated pre-2017 and 2018 surveys are given in Figure 2.

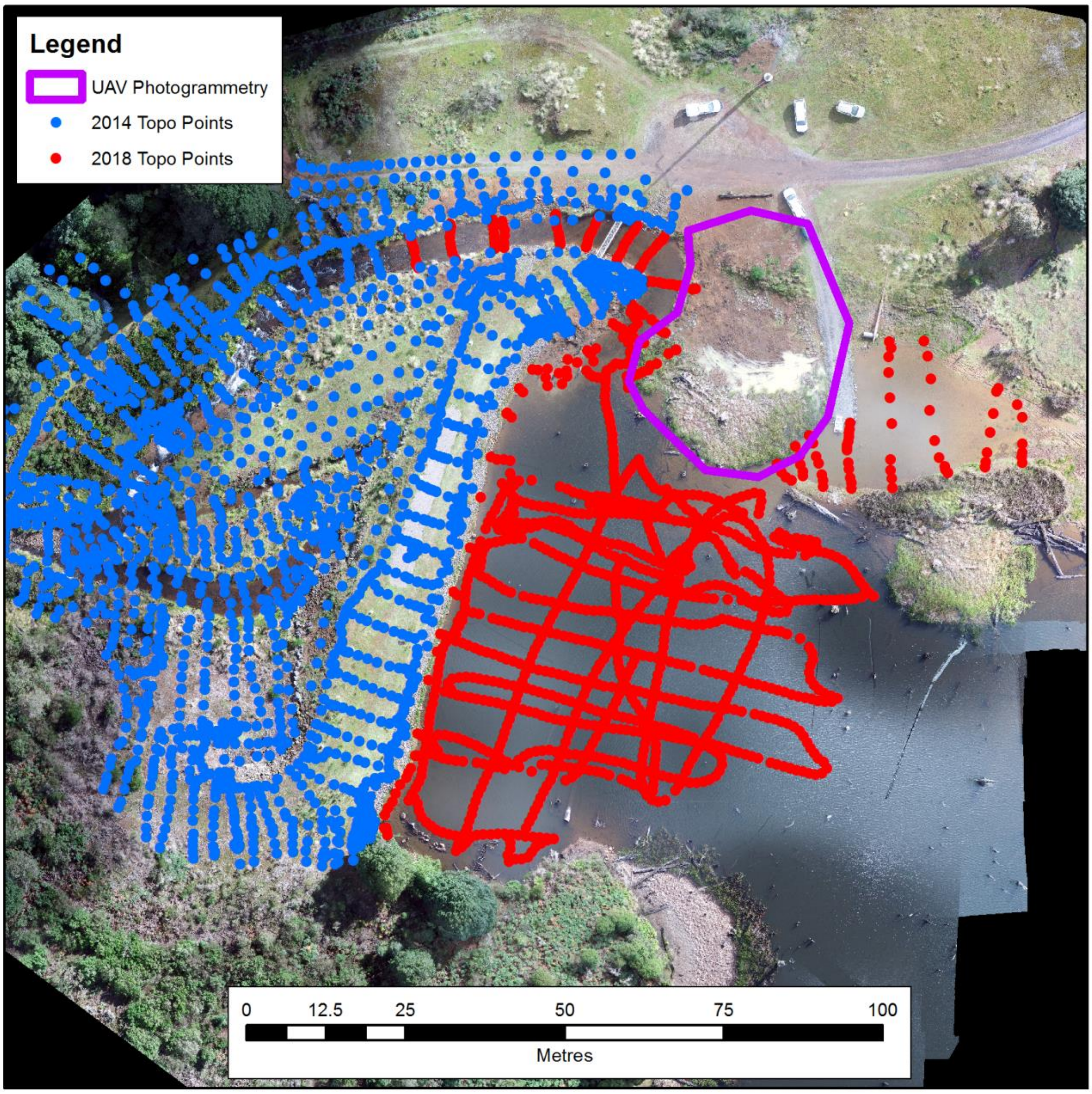

Figure 2 Extents of 2014 (blue) and 2018 (red) survey; the survey was augmented with photogrammetry captured by unmanned aerial vehicle (UAV; purple region)

The HEC-RAS software package (version 5.0.3) was used to construct a rating for the spillway using a 1-dimensional hydraulic model developed from the pre-2017 survey of the spillway channel. Cross-sections were selected to represent the approach from the reservoir to the crest in the spillway channel, the spillway crest and also the downstream channel. As flow entering the spillway from the reservoir may not perpendicular to the entry channel a 2-dimensional hydraulic model was also constructed to validate the rating. This 2-dimensional model was run for three design discharges: 5 m^3/s, 10 m^3/s, and 20 m^3/s. Both models used a Manning's n value of 0.03 to represent the roughness of the spillway channel downstream of the crest of the spillway. This roughness value is representative of an excavated channel with an earth bottom and rubble on site sides (Table 5.6, Chow, 1959). The minimum and maximum values for this channel type are 0.028 and 0.035. A sensitivity analysis using the upper range Manning's n value of 0.04 found little impact on the rating.

The approach channel of the spillway has been assigned a Manning's n value of 0.08, and the upper part of the channel has a Manning's n of 0.06; these are based on extensive weed growth present in channel (Figure 3).

Figure 3 The reservoir and approaches to the spillway. The dam wall is to the right of the photo. Note considerable weed growth in the region.

The extents of both models are given in Figure 4.

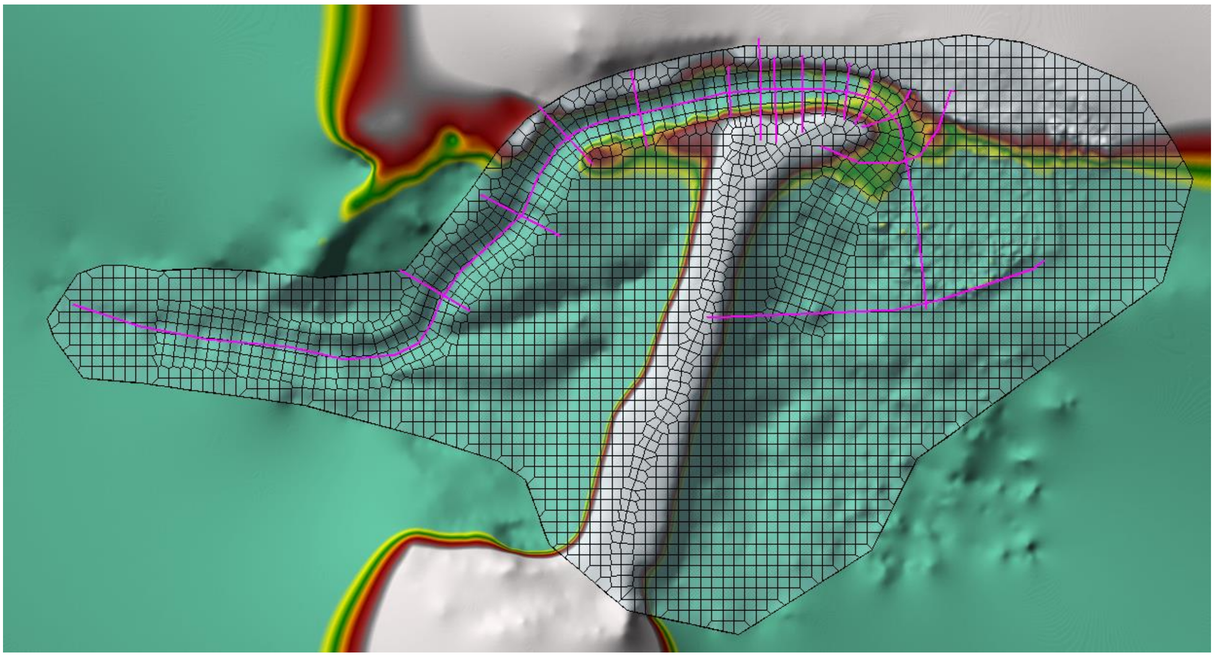

Figure 4 Extents of the 1-dimensional model (pink profile and cross sections) and 2-dimensional model (black lattice) for Waratah spillway

The derived spillway rating is given in Figure 5 and illustrates that the spillway had a capacity of approximately 15 m^3/s before the dam crest (607.5 m AHD) is overtopped. This is considerably different to Hydro Tasmania Consulting's (2010) estimate of 5.3 m^3/s (when water in the reservoir exceeds the spillway invert by 0.8 m). Reasons for the differences are:

- The current estimates of water level at the dam crest above the spillway invert (1.2 m) exceed the previous estimates (0.8 m) by 50% (see Table 1)
- The hydraulic modelling approach is considerably more rigorous than the previous estimate using the broad crested weir equation

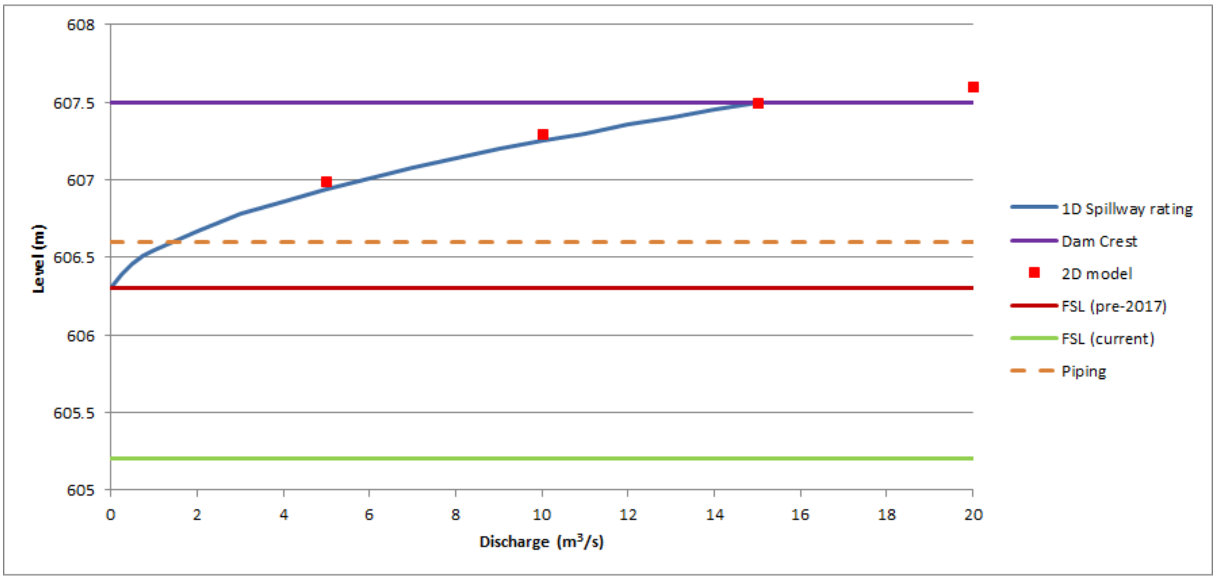

Figure 5 Derived spillway rating for Waratah Dam in the pre-2017 condition

It is evident that the spillway capacity is ~1.5 m^3/s when the reservoir reaches the level of the known piping hole in the embankment.

Flood frequency analysis

Due to the absence of data at the site, regional methods and data from nearby gauging stations have been used to estimate peak inflow to the dam site. The Australian Rainfall and Runoff (ARR) Regional Flood Frequency Estimation (RFFE; Engineers Australia 2017) method has been used to estimate the inflow flood frequency to at Waratah Dam. This has been compared with flood frequency estimates transposed from two nearby gauges: Hellyer River at Guildford Junction (Hydro Tasmania; catchment area of ~100 km^2) and Claytons Rivulet (DPIPWE; catchment area of ~13 km^2). Hellyer River was selected as it is adjacent to the Waratah Catchment, and Claytons Rivulet was selected as it has a similar catchment area to Waratah Dam. Records for these sites have been obtained from the Bureau of Meteorology (2018). Log-Pearson Type III flood frequency distributions were fitted to the annual series of these records and transferred to the Waratah catchment using the method described by Entura (2017b). These estimates were also compared to those derived using the Tasmanian Regional Method (Smythe & Cox 2006) as shown in Table 2.

Table 2 Comparison of inflow (no dam condition) flood frequency estimates derived from different methods (peak flows are given in m^3/s)

AEP (1:X)	RFFE (AR&R 2016)	Hellyer River transferred	Claytons Rivulet transferred	Tas. Regional Method[3]
2	**4.7**	4.3	3.2	
5	**7.09**	6.1	4.8	
10	**8.87**	7.3	5.8	
20	**10.7**	8.5	6.6	
50	**13.3**	10.3	7.5	16
100	**15.5**	11.7	8.2	19

The Tasmanian Regional Method (Smythe & Cox 2006) is no longer regarded as current, and has been superseded by the RFFE. Furthermore, Hydro Tasmania Consulting (2010) noted that the Tasmanian Regional Method estimates could be conservative, which is confirmed by the comparison given in Table 2. The Australian Rainfall and Runoff Regional Method estimates have been adopted for this study as they are the most conservative of the methods that are current.

Rainfall/runoff model development

A rainfall-runoff event (initial loss/continuing loss[4]) model representing the catchment and reservoir has been adapted from an existing yield model of Waratah Dam (Entura 2017a). As there is no streamflow data available in the catchment, model parameters were initially extracted from a recent study of Mikany Dam (Entura 2017b). The parameters were then modified to match the modelled

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[3] Given by Hydro Tasmania Consulting (2010)

[4] Referred to as IL/CL

peak inflows to the flood frequency. Design rainfalls and temporal patterns were used during the validation. The final parameters are shown in Table 3.

Table 3 Model parameters adopted in this study

Parameter	Value
Alpha (channel attenuation)	0.75
Beta (catchment attenuation)	0.75
n (channel non-linearity parameter)	0.8
m (catchment non-linearity parameter)	0.8
IL (initial loss)	2.5 mm
CL (continuing loss)	2.5 mm/hour
Baseflow	0.5 m^3/s
Start storage level	606.4 m

The storage curve from Figure 1 and the spillway rating from Figure 5 have been used in the reservoir routing component of the model. The dewatering outlet is assumed to not be operating for all model runs. The start storage level for the model runs has been taken as the median water level (50% exceedance) of the reservoir in this state, taken from the storage duration curve (Entura 2017). This level is 0.1 m above the spillway invert, ie 606.4 m. The baseflow for the model has been determined by from the outflow at this level using the spillway rating (Figure 5) and assuming that inflows will equal this This estimate differs marginally from the median inflow yield of 0.3 m^3/s as determined by Entura (2015).

Model validation

Although there is no at-site hydrometric timeseries data available at Waratah Dam, it is important to validate the model to whatever at-site observations have been made. Qualitative information has value in these circumstances. There is anecdotal evidence that during the flood on 6th June 2016, reservoir levels reached the dam crest (see photos in Figure 6). This was a rare storm event which caused significant damage across Tasmania, particularly in the North West. Rain gauge data has been obtained from Hydro Tasmania's Waratah site (site number 1459). During this event, the maximum 24-hour rainfall recorded was approximately 195 mm. The total event rainfall was recorded as 218 mm over a 48 hour period.

The observed Waratah rainfall data was used to model the 6th June 2016 event using the parameters given in Table 3. A uniform spatial rainfall pattern across the catchment was applied.

The modelled peak reservoir level was 607.49 m (hydrographs are provided in Figure 7), confirming that the model is representative of the catchment, reservoir and spillway.

The annual exceedance probability (AEP) of the point 24 hour rainfall depth of 195 mm is approximately 1:500, when compared with design rainfalls from the Bureau of Meteorology for this site (BoM 2016). It is possible that this storm could have an embedded burst at a shorter duration with a rarer AEP. This has not been investigated due to scope constraints of this project.

Figure 6 Waratah Dam (left) and its spillway (right) during the event on 6th June 2016; the flood is in recession at the time these photos were taken

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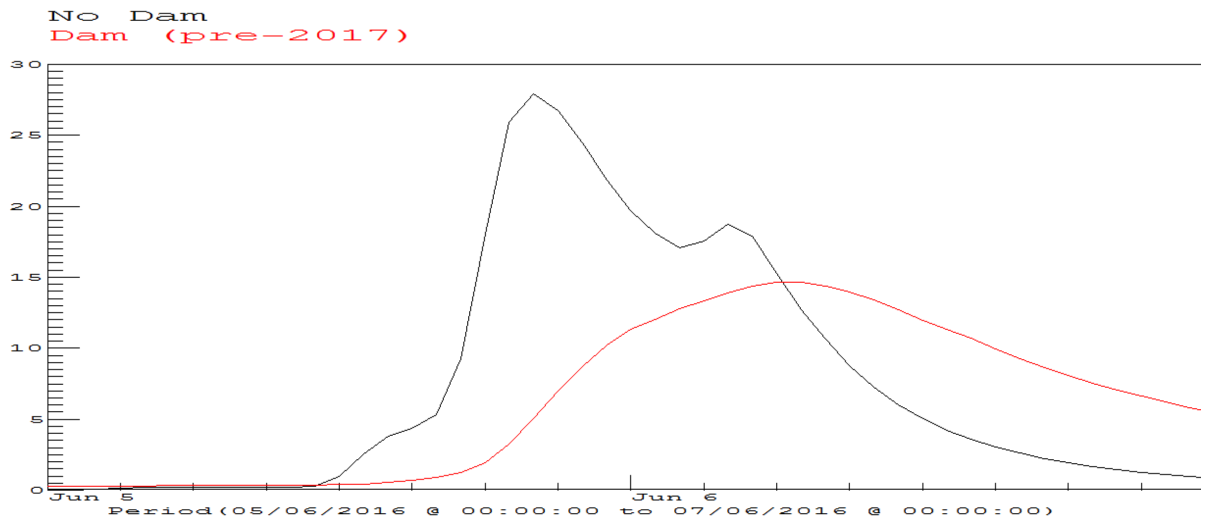

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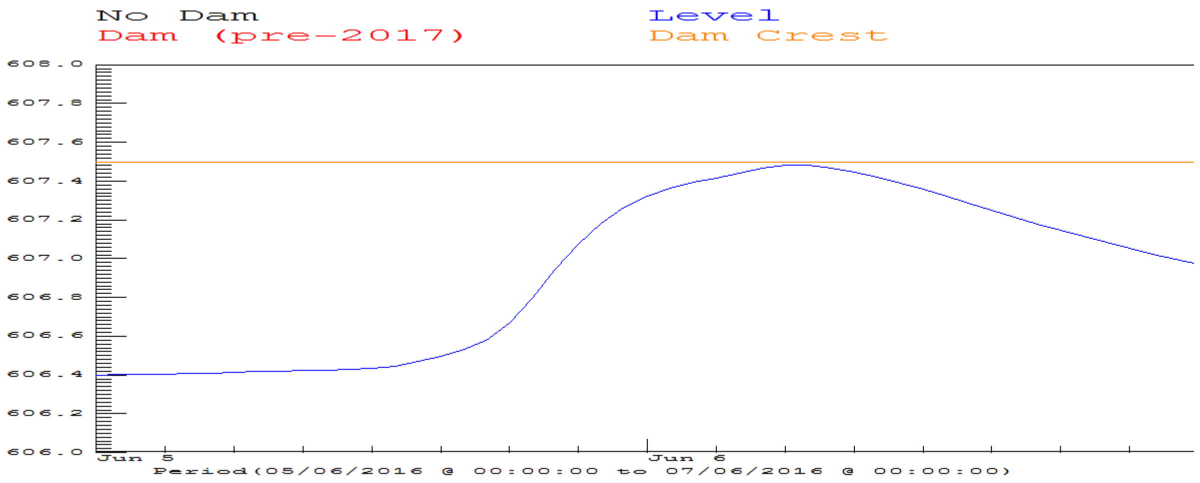

Figure 7 Modelled (a) inflow and outflow hydrographs (units: m^3/s) and (b) water level (units: m) for the event on 6th June 2016

Rainfall/runoff model results

The model has been run using storm burst design rainfalls with an ensemble of temporal patterns, sourced from Geoscience Australia (2017). Ten 'point' temporal patterns and a uniform spatial pattern (due to the small size of the catchment) for a range of design storm durations between 6 and 120 hours. Design storm durations between 0.5 and 6 hours were also used in the no-dam condition for the 1:50 and 1:100 AEPs, which verified that these shorter durations were not critical for determining peak discharge with the catchment in its natural condition. Design rainfall depths were obtained from the BoM (2016).

Losses were varied by AEP as described by Australian Rainfall and Runoff (Ball et al 2016 – Book 8 Sections 4.3.2.2 and 4.3.4.2), between the 1:100 AEP and the AEP of the PMP (probable maximum precipitation), which was estimated to be $1:10^7$ (Ball et al 2017; Book 8 Section 3.4.2) for the Waratah Dam catchment. The losses are given in Table 4.

Although the 2016 event was found to suitable with the full loss values (Table 3) and had an estimated rainfall AEP of 1:500, it was decided that there was insufficient information from this event to adjust losses outside of the Australian Rainfall and Runoff recommendations.

Table 4 Losses varied by AEP for design event modelling

AEP (1:X)	IL (mm)	CL (mm/hour)
50	2.5	2.5
100	2.5	2.5
200	1.64	1.64
500	0.94	0.94
1000	0.62	0.62
2000	0.41	0.41

Design flood peaks and levels for the no dam and pre-2017 condition, for a range of AEPs, are given in Table 5.

It should be noted that for design storm durations longer than 6 hours, there is considerably more variability on peak discharge due to temporal pattern than there is for design storm duration. As such, the critical durations listed in Table 5 should be regarded as notional; similar peaks are achieved from a range of design storm durations.

The discharge record at Clayton's Rivulet, which has a similar size catchment to Waratah Dam, shows that the largest events in a non-dam catchment typically last greater than 1 day. This adds confidence that similarly long design storm durations may be critical to peak discharge for the catchment in its no-dam condition.

The AEP of a dam crest flood is estimated to be 1:400; however, due to the variability of storm temporal pattern on peak reservoir level, the dam crest can be overtopped in some modelled 1:200 AEP storms.

Table 5 Design flood peaks and levels for Waratah Dam; based on median modelled values

	No dam condition		Dam in pre-2017 condition		
AEP (1:X)	Peak discharge (m^3/s)	Notional critical duration (hours)	Peak discharge (spill; m^3/s)	Peak reservoir level (m)	Notional critical duration (hours)
50	13.0	9	6.5	607.04	72
100	15.0	72	8.0	607.14	72
200	20.5	36	12.0	607.36	36
500	26.8	36	17.7	607.55	36
1000	31.4	36	22.1	607.64	36
2000	35.9	36	26.4	607.73	72

The focus of this study is to determine the attenuation impact of the reservoir. As such, it is important to compare the difference in peaks for the no-dam and with dam scenarios for specific events. This is presented in Table 6 for mid-range events for critical durations to the no dam peak and for the dam in the pre-2017 condition for AEPs of 1:50 and 1:100.

Table 6 Attenuation of specific design events at the 1:50 and 1:100 AEP

AEP (1:X)	Design storm duration	Condition that duration is critical for	Peak outflow (m^3/s) with no dam	Peak outflow (m^3/s) with dam in pre-2017 condition	Peak level (m) with dam in pre-2017 condition
50	9 hours	No dam	13.3	4.7	606.92
50	72 hours	No dam and pre-2017	12.7	6.4	607.00
100	72 hours	Pre-2017	15.4	8.0	607.14

To assess the sensitivity of peak discharge to temporal patterns, an ensemble of 10 temporal patterns per design storm duration have been modelled (Figure 8); it is evident that the peak level of a storm is very dependent on the storm's temporal pattern. This is also illustrated by event hydrographs shown in Figure 9, where a 1:200 AEP event has a similar peak level/outflow to a 1:500 AEP event.

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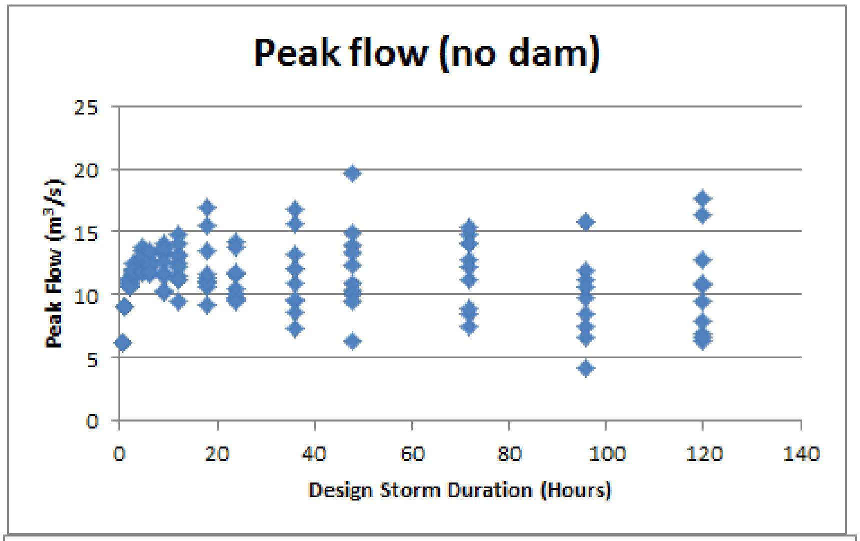

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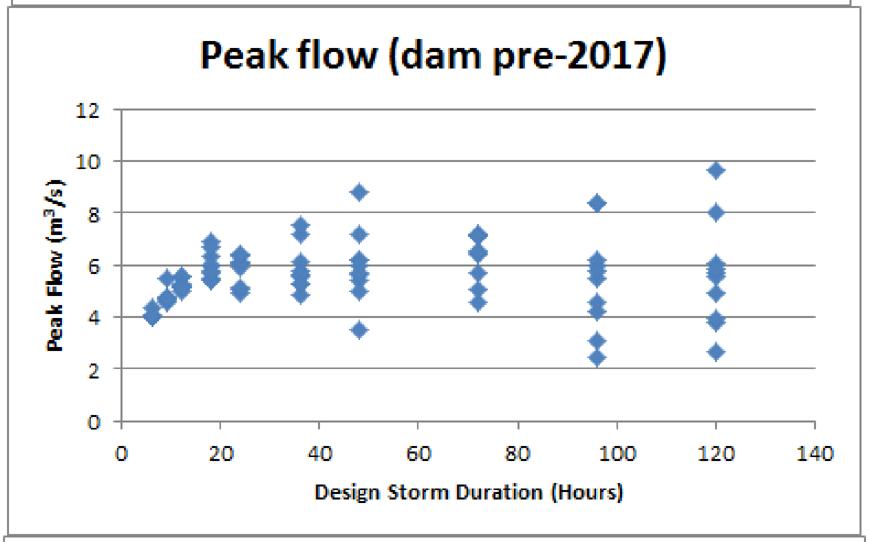

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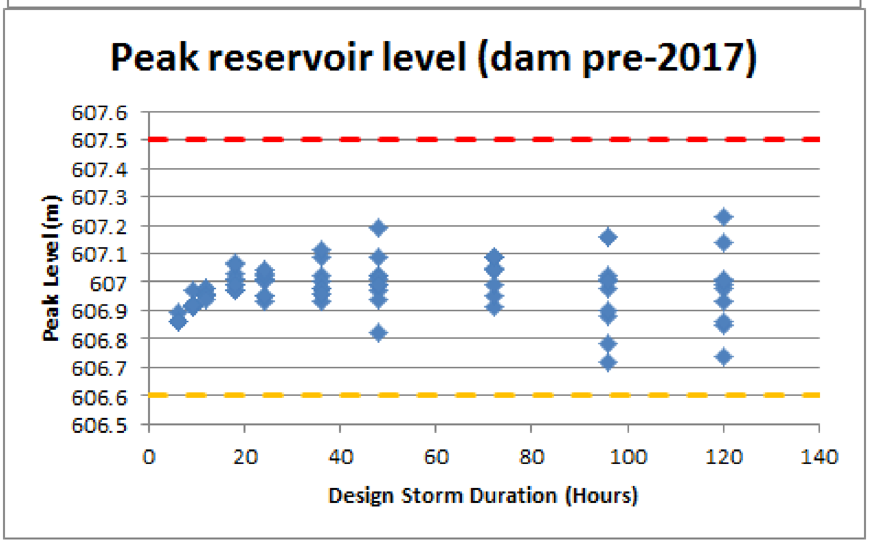

Figure 8 Peaks for 1:50 AEP design rainfalls for all ensembles of temporal patterns at each design storm duration for (a) inflow without the dam; (b) outflow from the dam in the pre-2017 condition; and (c) level in the dam (with level of piping given as orange dash and dam crest as red dash) in the pre-2017 condition. It is notable that all scenarios exceed the level of piping at the 1:50 AEP

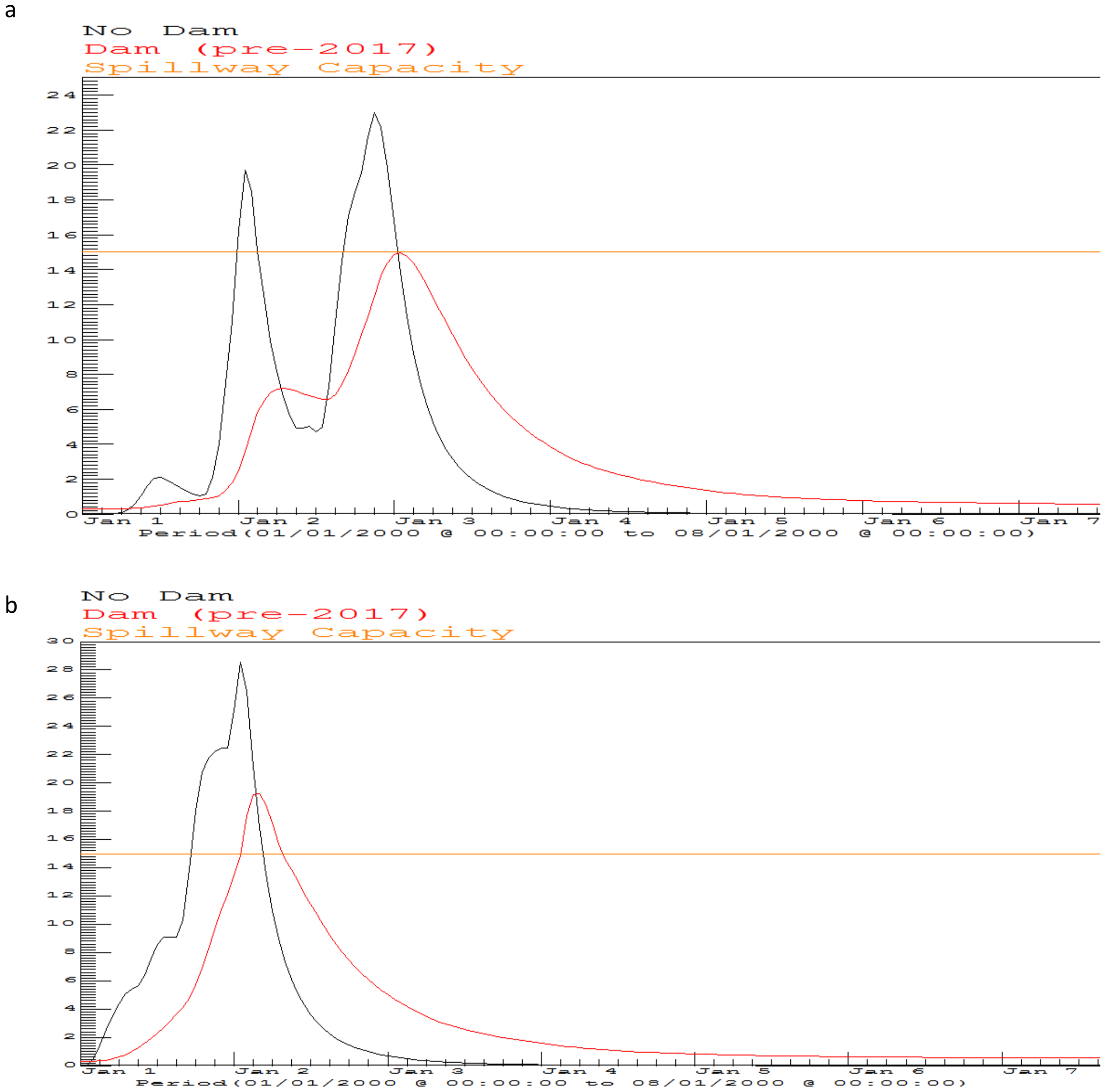

Figure 9 Hydrographs (units: m^3/s) in the no dam (black) and dam in the pre-017 condition; (a) a 1:200 AEP 48 hour design rainfall event that results in a peak reservoir level at 607.5 m (ie that reaches the dam crest) and (b) a 1:500 AEP 24 hour design rainfall event that exceeds the dam crest

Conclusions

There are substantial limitations regarding available information at Waratah Dam, including the lack of at-site hydrometric data, limitations in the estimates of the storage-volume rating, and the need to transfer flood frequency estimation from other sites and using the regional method as a fall-back. Despite this, it is believed that the model developed as part of this project has a good representation of the catchment and reservoir, given that it matches the adopted flood frequency distribution and is replicates estimates of peak level estimated from anecdotal evidence of the flood dated 6th June 2016. However, it is noted that given the broad range of temporal patterns that a large storm could exhibit, there is considerable uncertainty in the design flood levels.

Waratah Dam, with the spillway in its pre-2017 condition, does attenuate flood peaks. The magnitude of attenuation varies considerably due to different storm conditions (duration, intensity/depth and temporal pattern).

The reservoir is more likely to attenuate flooding under any of the following conditions:

- The start storage of the reservoir is low
- The duration of the storm is short
- The rainfall depth is small, or in other words the AEP (annual exceedance probability) of the event is more frequent

It is not known what level of flooding at Waratah Dam is likely to have any impact in downstream communities. In order to assess this, a floodplain study of the downstream regions of interest would be required.

The median AEP of a dam crest flood at Waratah is estimated to be 1:400 AEP. The dam crest was also exceeded in some models with a design rainfall AEP of 1:200. Given that this is assessed with zero freeboard, and the variability of peak level due to the variability of storm characteristics, the flood capacity of the dam is inadequate for its Significant Consequence Category. ANCOLD (2000) recommended flood capacity requirements for a Significant Consequence Category dam are between 1:1,000 and 1:10,000 AEP plus freeboard for wave action.

Additionally, there is a significant piping failure risk with all modelled events at 1:50 AEP exceeding the level of the known pipe in dam at RL606.6 m AHD; the estimated AEP of exceeding this level is between 1:2 and 1:5. For this reason, the level of the dam should be maintained below this level with a very low probability of being exceeded during a flood.

Acknowledgements

Thanks are owed to the Bureau of Meteorology (BoM), Hydro Tasmania, and the Department of Primary Industries, Parks, Water and Environment for gauged data used in this study; data has been obtained through BoM's Water Data Online tool and directly from Hydro Tasmania's HydstraTSM database.

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